



The Development of Environmental Barrier Coatings for SiC/SiC Ceramic Matrix Composites: Challenges and Opportunities

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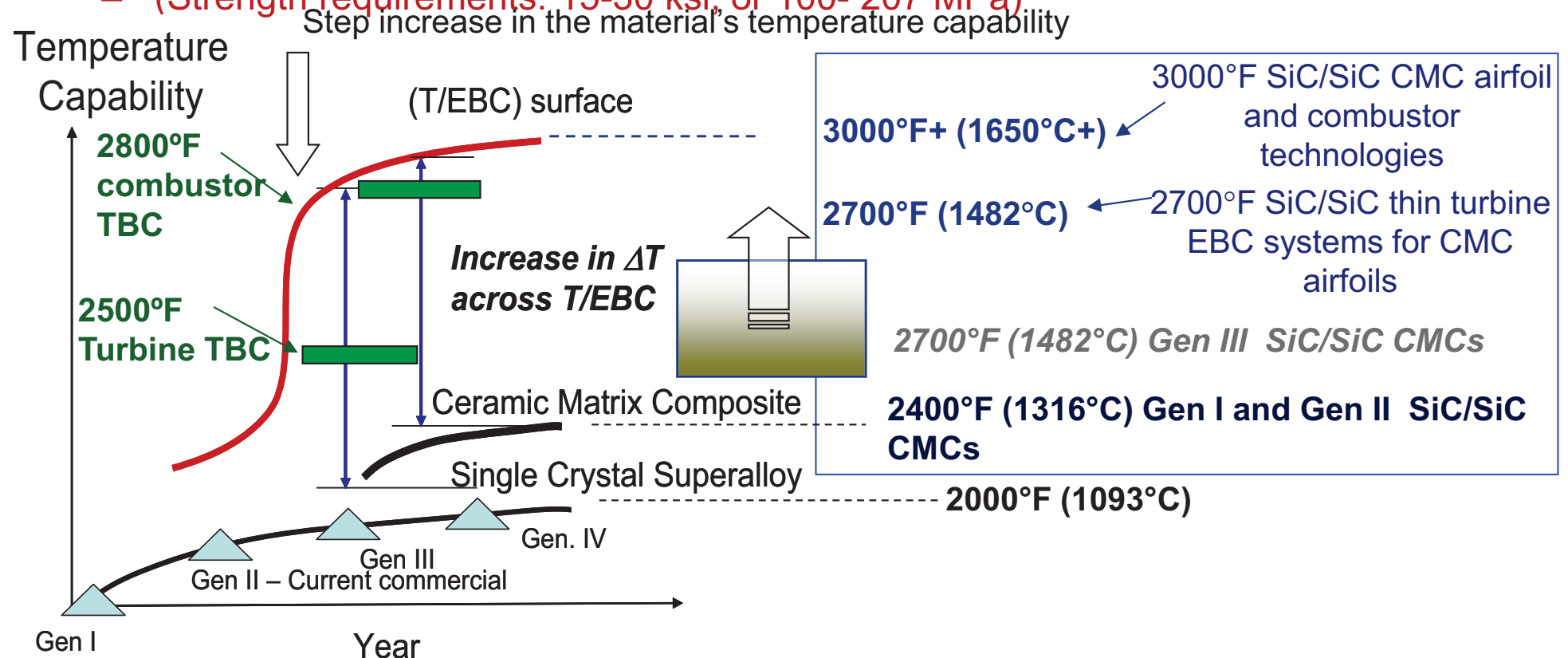


Outline

- **Environmental barrier coating (EBC) system development: needs and challenges**
- **Advanced environmental barrier coating systems for SiC/SiC ceramic matrix composite (CMC) airfoils and combustors**
 - NASA coating development goals
 - Current turbine and combustor EBC coating development emphases
 - Coating design issues and performance evaluation
- **Development of next generation environmental barrier coatings**
 - Advanced processing
 - Subelement and subcomponent demonstrations
- **Summary and emerging opportunities**

NASA EBC and CMC System Development

- Emphasize temperature capability, performance and *long-term* durability
- Develop innovative coating technologies and life prediction approaches
- 2700°F (1482°C) EBC bond coat technology for supporting next generation
- 2700-3000°F (1482-1650°C) **thin** turbine and CMC combustor coatings
 - **Recession: <5 mg/cm² per 1000 h**
- Highly loaded EBC-CMCs capable of thermal and mechanical (static/low cycle and dynamic) loading
 - **(Strength requirements: 15-30 ksi, or 100- 207 MPa)**

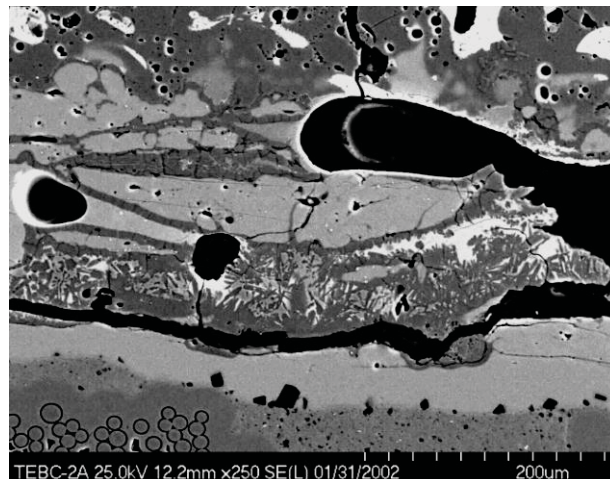
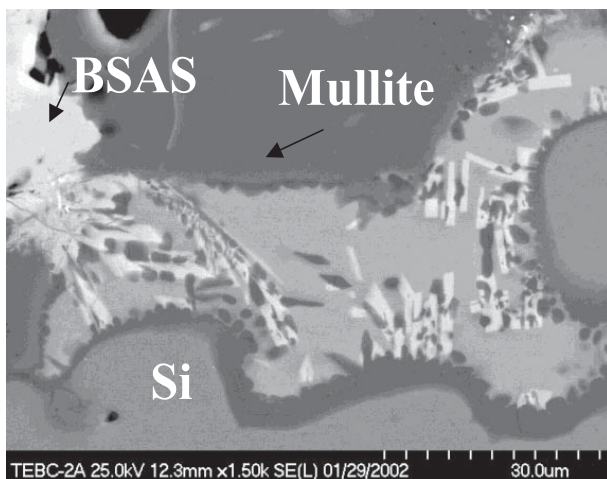




Environmental Barrier Coating Development: Challenges and Limitations

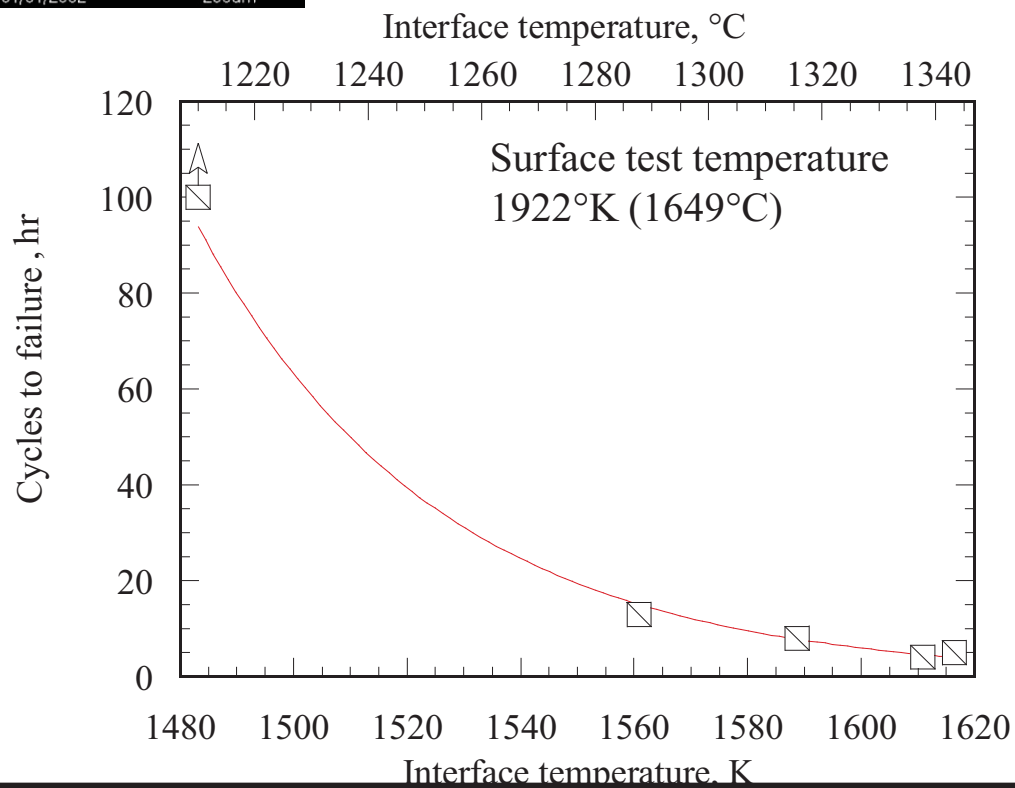
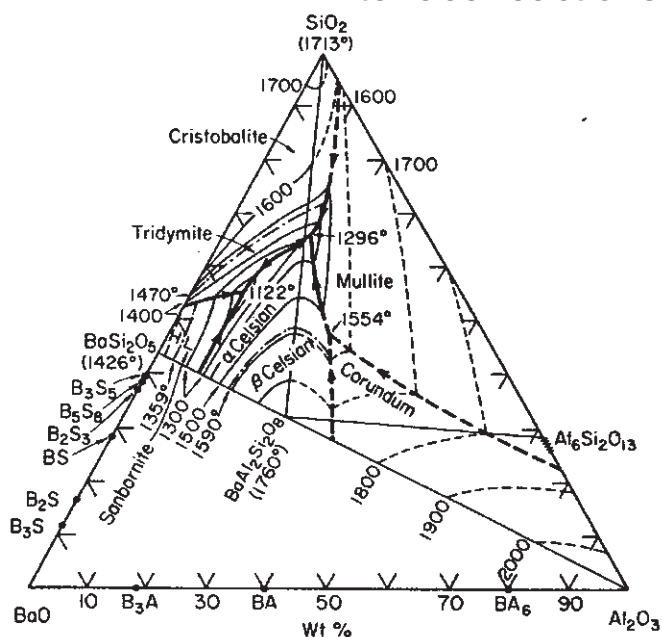
- Current EBCs limited in their temperature capability, water vapor stability and long-term durability, especially for advanced high pressure, high bypass turbine engines
- Advanced EBCs also require higher strength and toughness
 - Resistance to combined high-heat-flux, engine high pressure, combustion environment, creep-fatigue loading interactions
- EBCs need improved erosion, impact and calcium-magnesium-alumino-silicate (CMAS) resistance and interface stability
 - Critical to reduce the EBC Si/SiO₂ reactivity and their concentration tolerance
- EBC-CMC systems need advanced processing for realizing complex coating compositions, architectures and thin turbine airfoil configurations for next generation high performance engines
 - Advanced high temperature processing of high stability nano-composites using Plasma Spray, EB-PVD and Directed Vapor EB-PVD, Plasma Spray - Physical Vapor Deposition

Environmental Barrier Coating Development: Challenges and Limitations



Various Advanced TEBC/mullite/mullite+BSAS/Si coat systems

Interface reactions at 1300°C



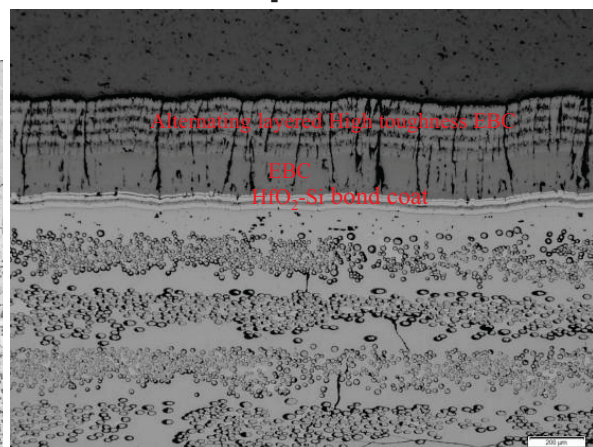
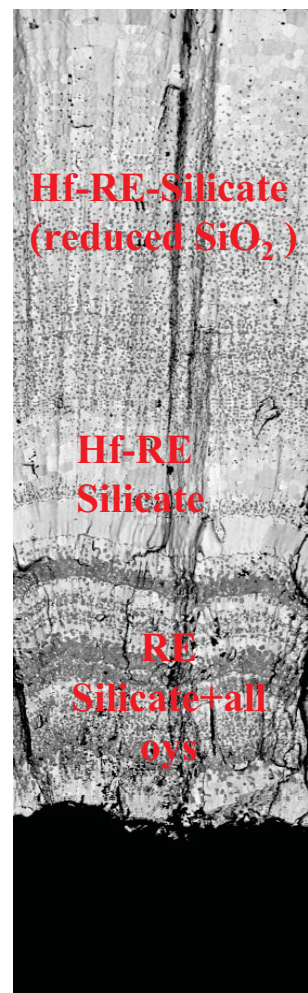


NASA Environmental Barrier Coating Technology Development - Continued

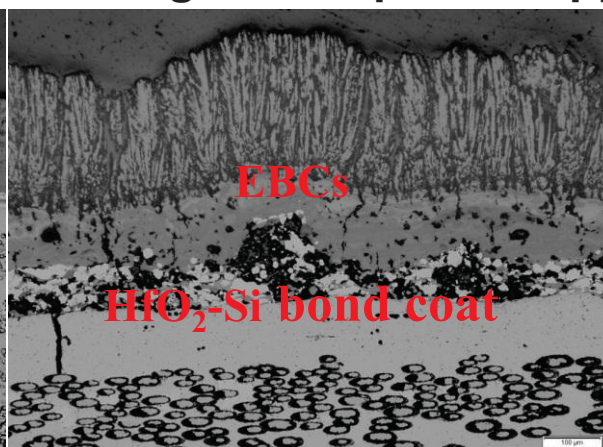
- Fundamental studies of environmental barrier coating materials and coating systems, stability, temperature limits and failure mechanisms
- HfO_2 and ZrO_2 - RE_2O_3 - $\text{SiO}_2/\text{RE}_2\text{Si}_{2-x}\text{O}_{7-2x}$ environmental barrier systems
 - Controlled silica content and transition element and rare earth dopants to improve EBC stability and toughness
 - Develop HfO_2 -Si based + X (dopants) and more advanced rare earth composite compound composition systems for 2700°F+ long-term applications
 - Develop prime-reliant composite EBC-CMC interfaces for fully integrated EBC-bond coat systems
- Processing optimizations for improved coating density and composition control robustness
- Develop advanced NASA high toughness, *Alternating Composition Layered Coating* (ACLC) compositions and processing for low RE t' low rare earth dopant low k HfO_2 and higher rare earth dopant silicates
 - Achieving high toughness has been one of key emphases for NASA coating technologies
 - Achieving high stability and recession resistance
 - Improve the resistance to CMAS and Volcano ash deposits

NASA Environmental Barrier Coating Technology Development – Continued

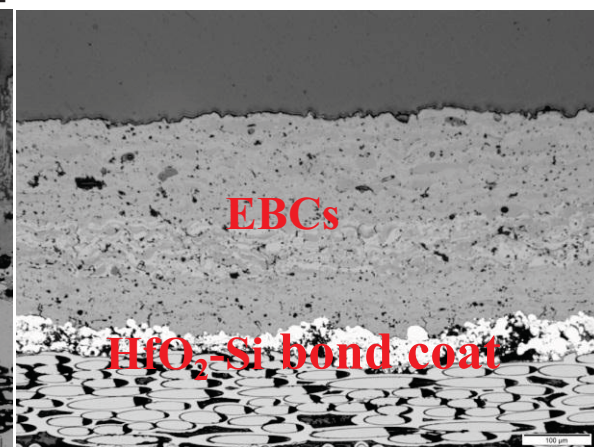
- Advanced EBC developments for various engine component applications



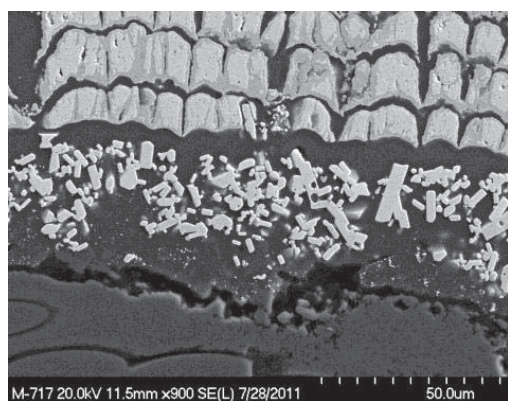
Electron Beam-Physical Vapor Deposited (EB-PVD) Turbine Airfoil EBCs



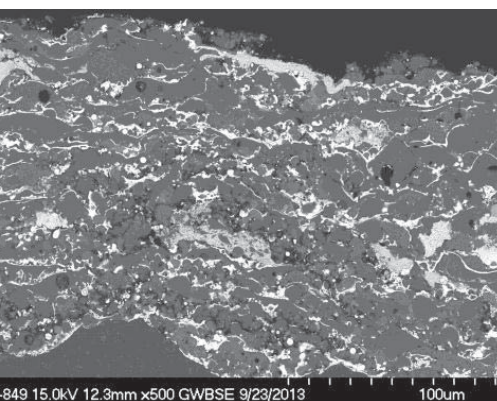
Hybrid EB-PVD) – Plasma Sprayed EBCs for turbine and combustor component



Plasma Sprayed EBCs for combustors

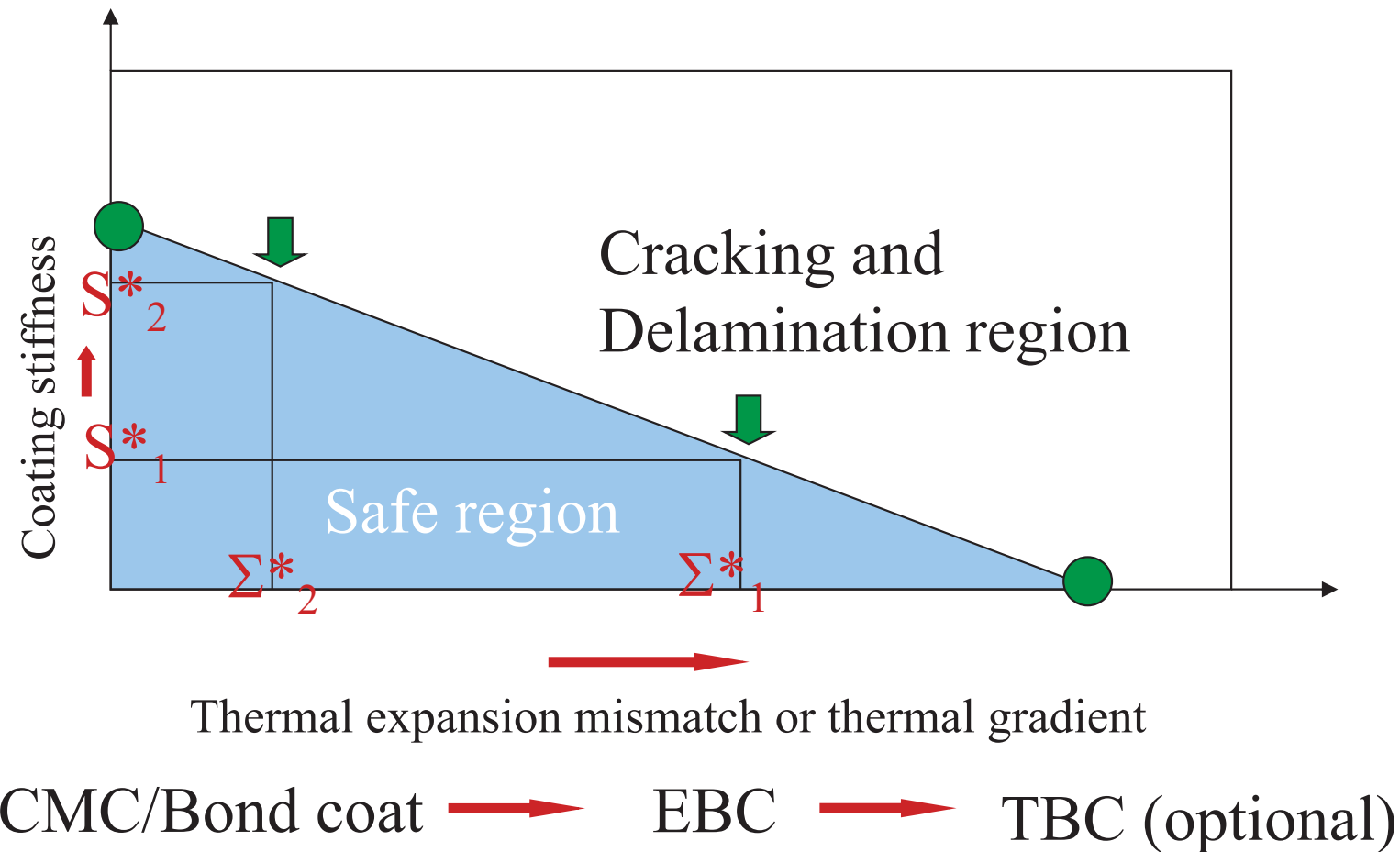


HfO₂-Si and alloyed EBC bond coats using EB-PVD processing: 2700°F temperature capability



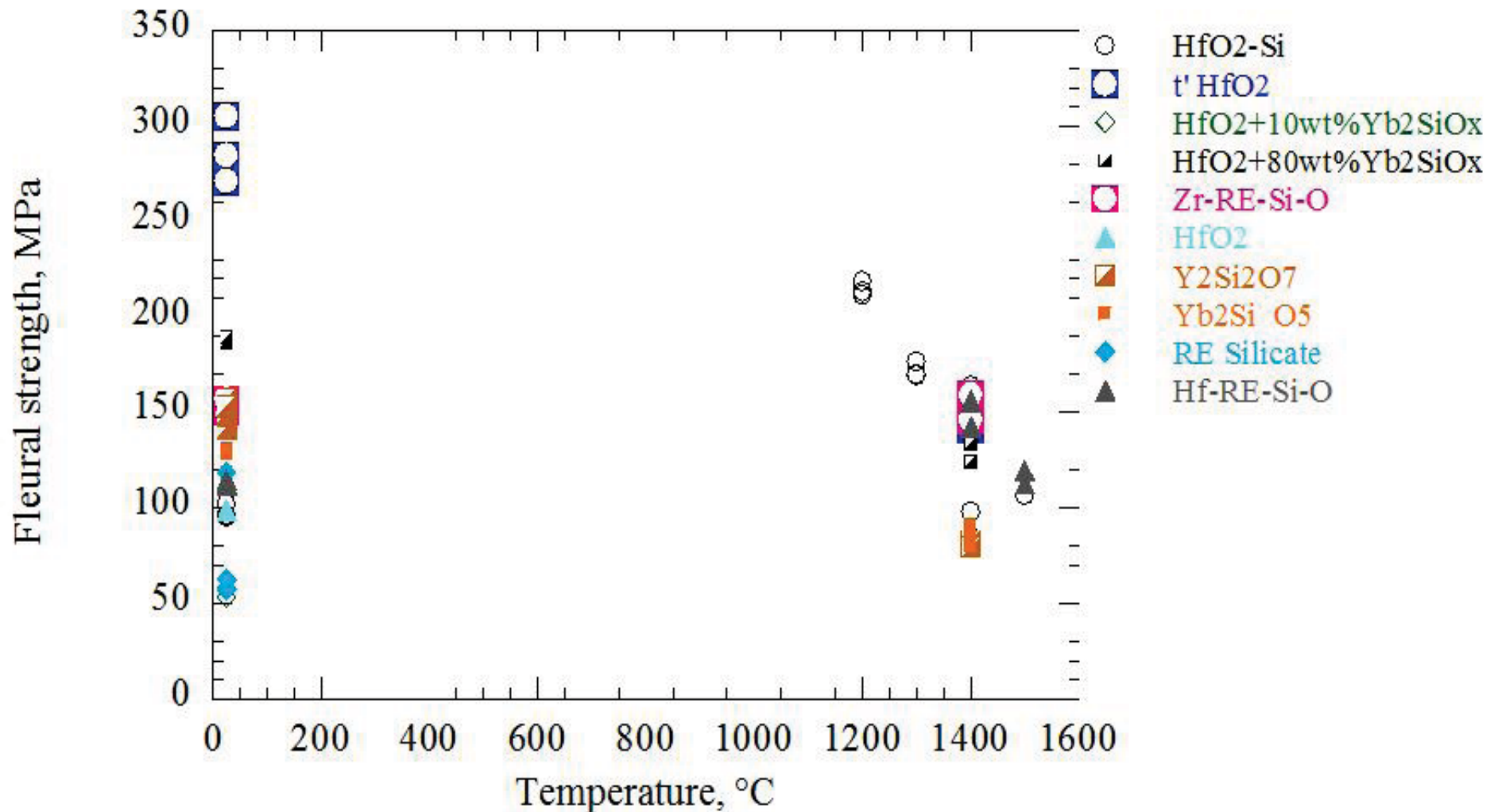
Plasma sprayed HfO₂-Si EBC bond coat

Coating Safe Design Approach



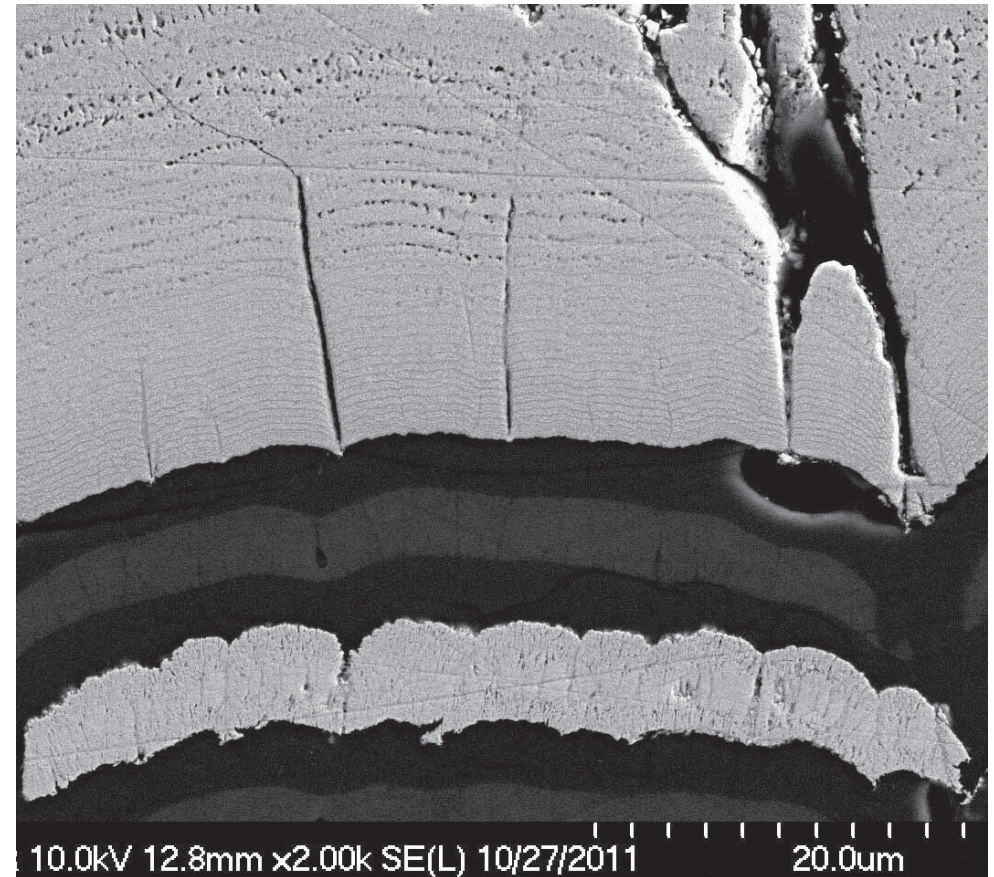
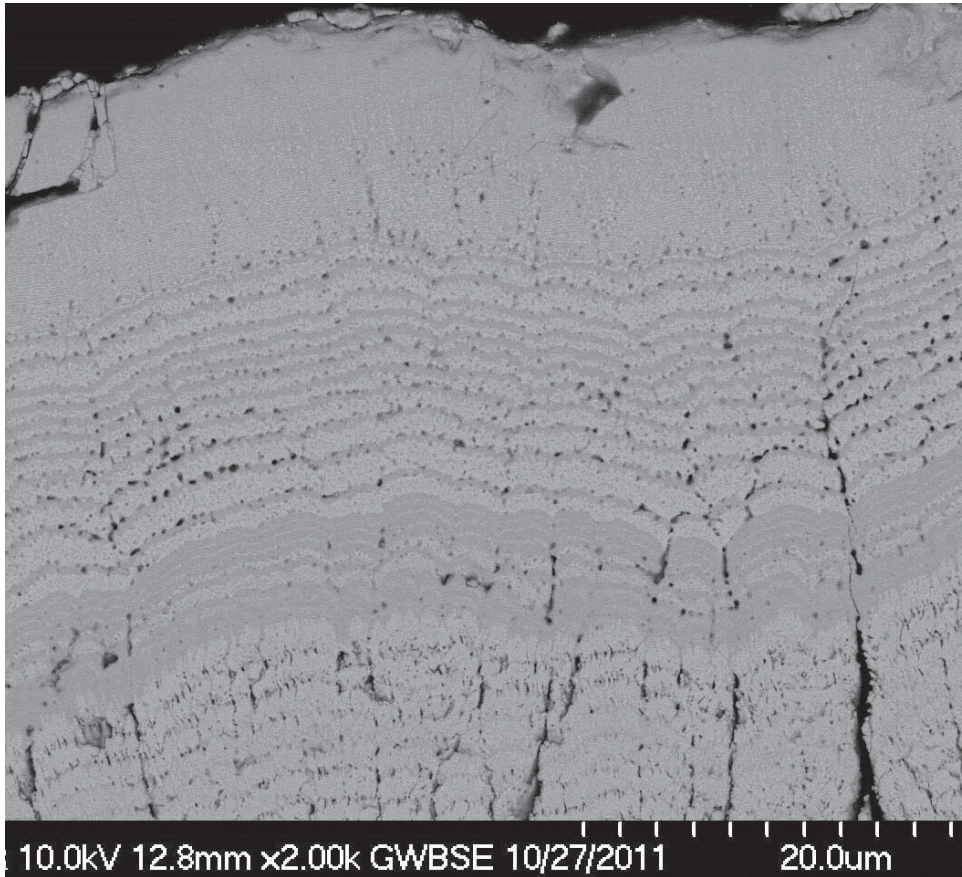
Advanced EBC System Strength Evaluations

- Evaluate and develop high strength and high toughness EBC materials
- Provide property database for design and modeling



Advanced EBC System Recession and Stability Evaluations

- Determining optimum compositions of in a high stability system consisting of (e.g., Yb, Gd, Y+Hf/Zr) silicates and oxide systems



Turbine airfoil EBCs: High pressure burner rig, at 10 atm, 2650°F

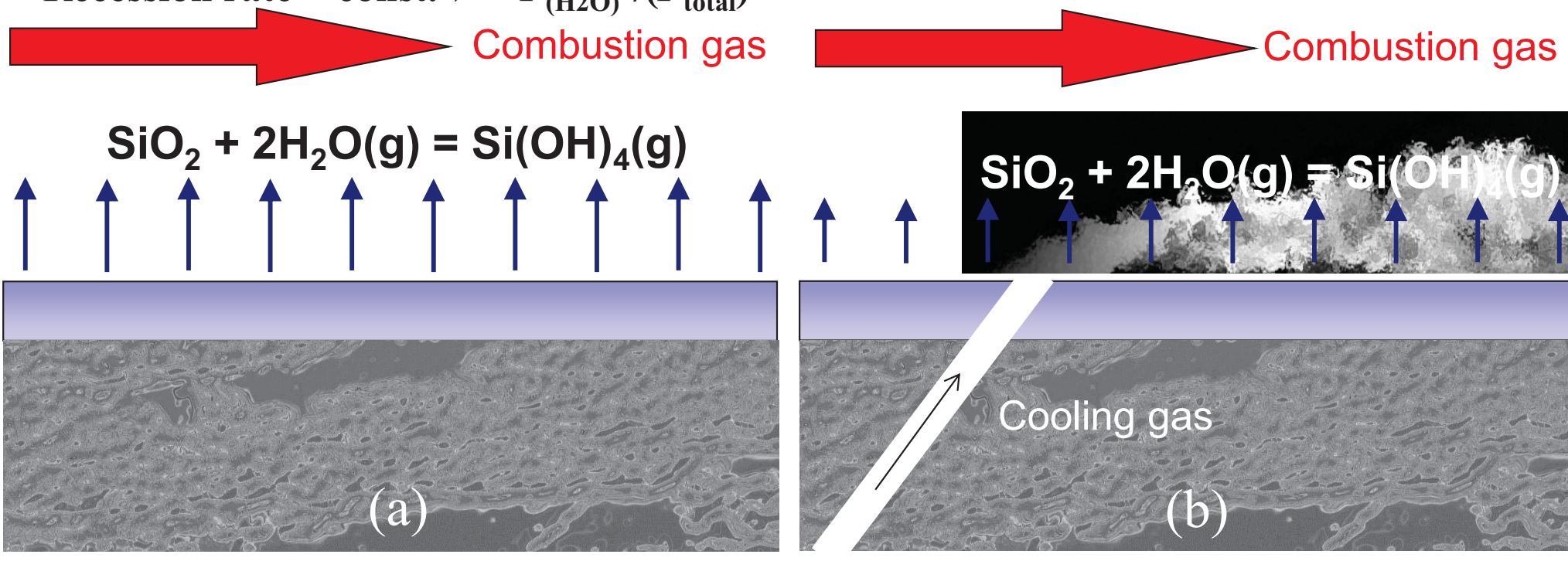
SiC/SiC and Environmental Barrier Coating Recession in Turbine Environments

- Recession of Si-based Ceramics

(a) convective; (b) convective with film-cooling

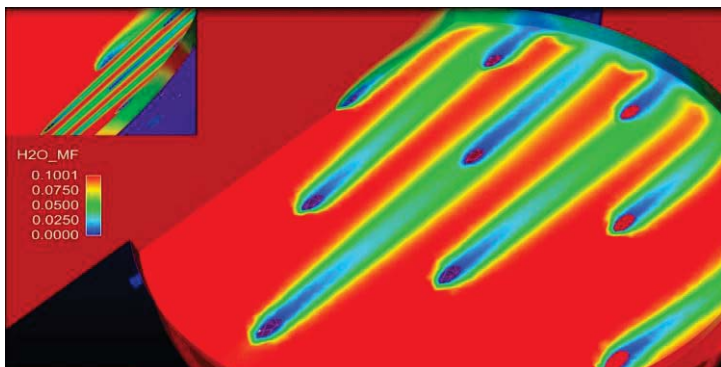
- **Advanced rig testing and modeling**, using High Pressure Burner Rig, coupled with 3-D Computational Fluid Dynamics (CFD) analysis, to understand the recession behavior in High Pressure Burner Rig

$$\text{Recession rate} = \text{const. } V^{1/2} P_{(\text{H}_2\text{O})}^2 / (P_{\text{total}})^{1/2}$$

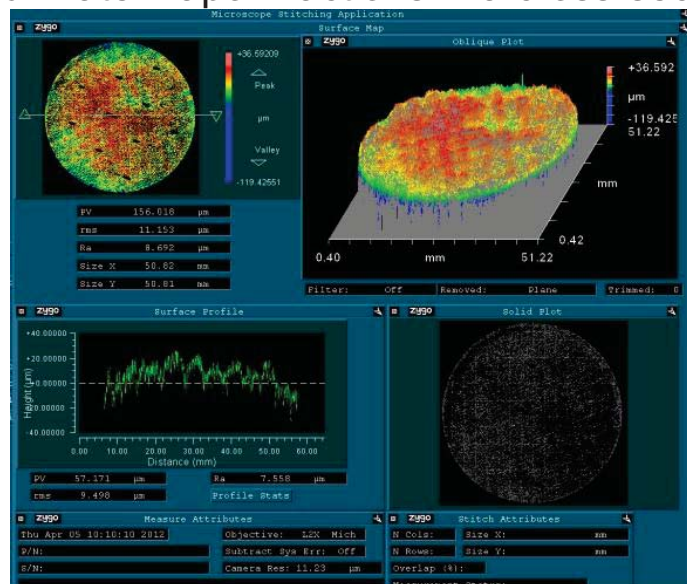


Recession of Film-Cooled SiC/SiC Specimens

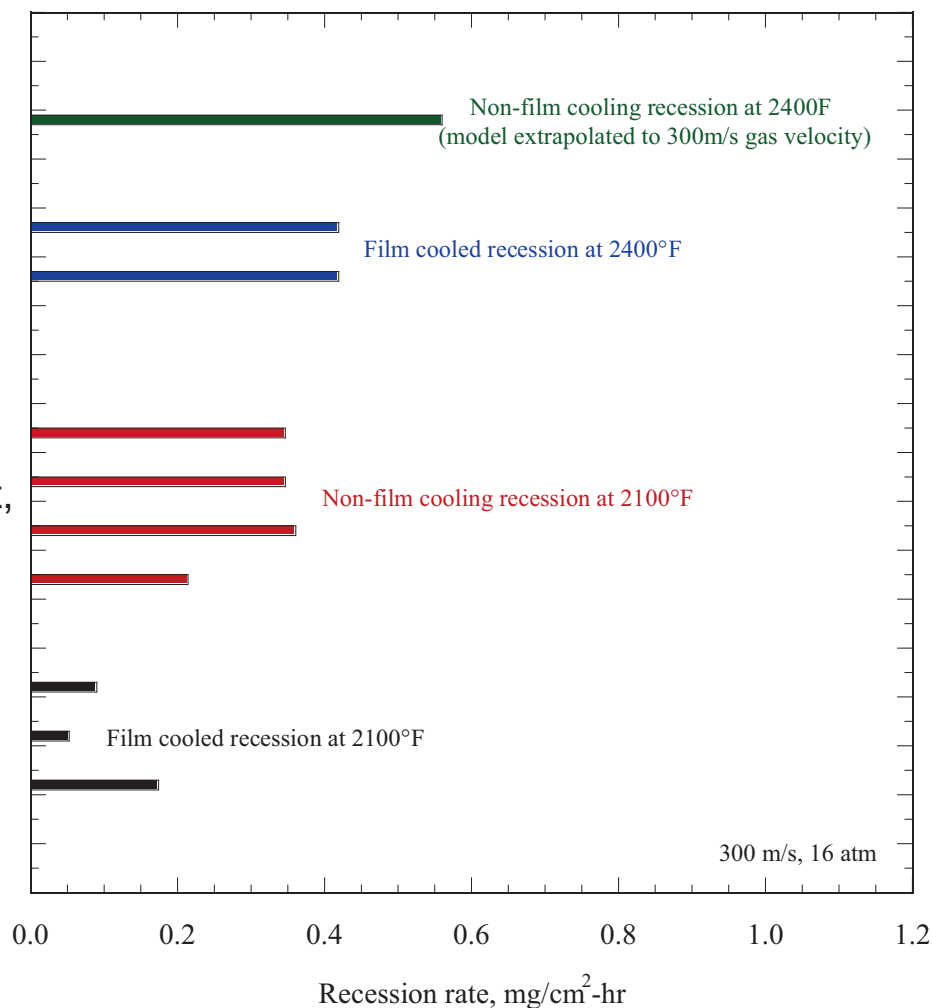
- Potentially improve EBC-CMC stability in combustion environments



The CFD modeling of a film cooled CMC 10 hole subelement, and water vapor fractions in a cross-section view



Zygo surface contour

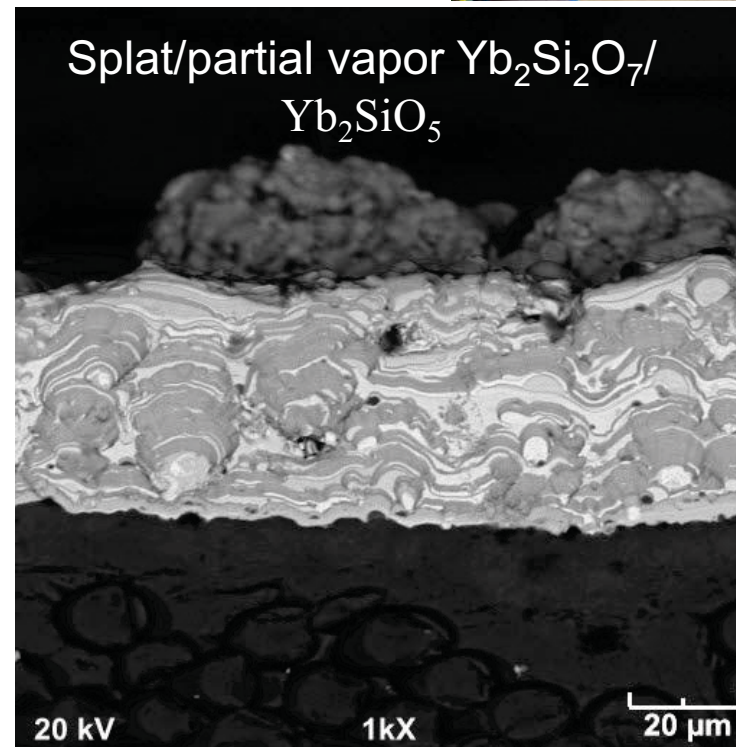
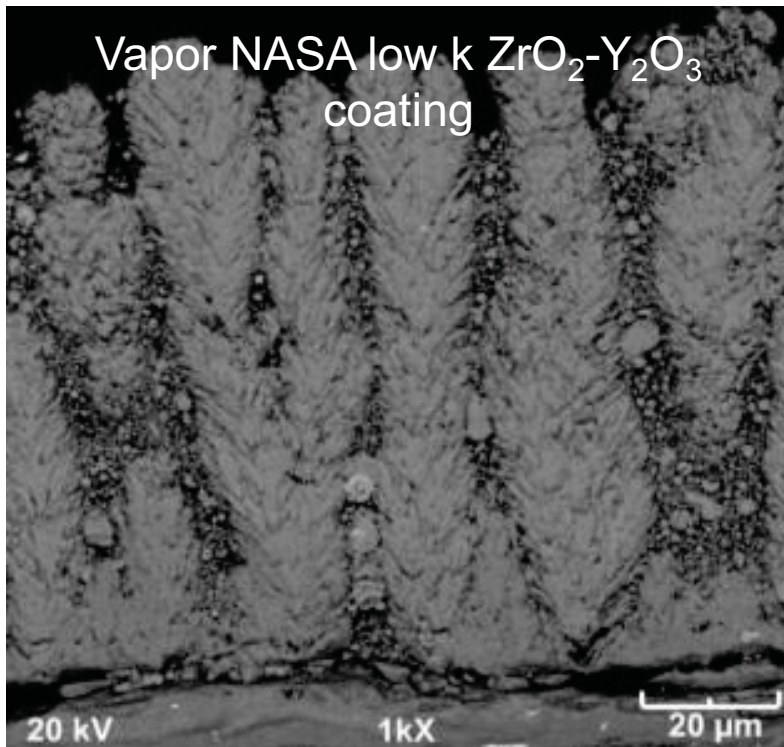


High temperature recession kinetics for film-cooled and non-film cooled SiC/SiC specimens tested at NASA High Pressure Burner rig

Plasma Spray - Physical Vapor Deposition (PS-PVD) for SiC-SiC CMC Airfoil Coating Processing

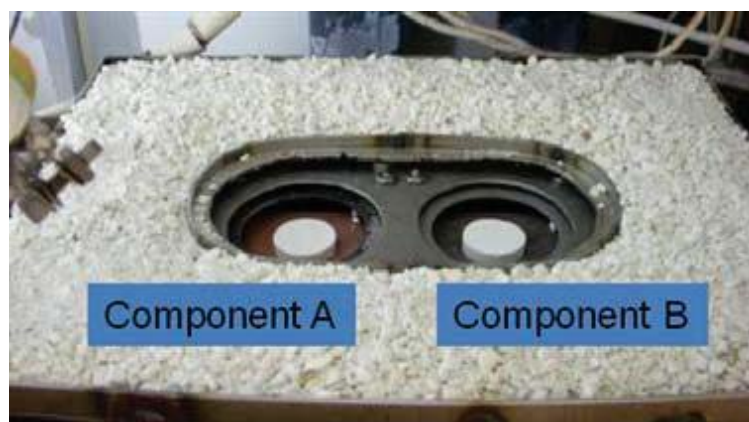
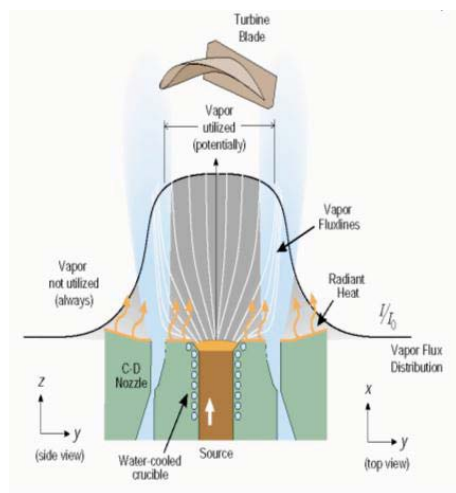
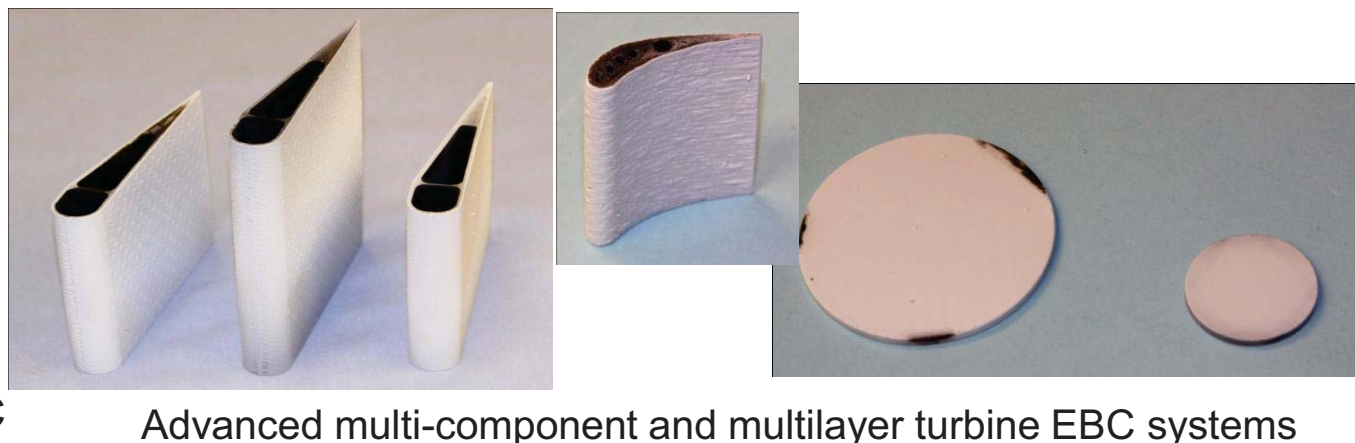
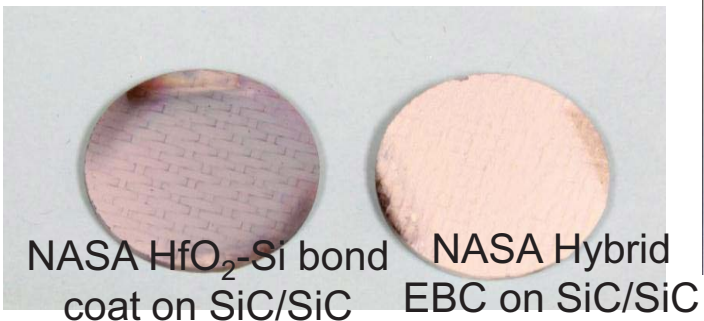
- Emerging processing methods developed by Sulzer Metco showing promise for next-generation SiC/SiC CMC turbine airfoil coating processing

NASA Hybrid PS-PVD
coater system

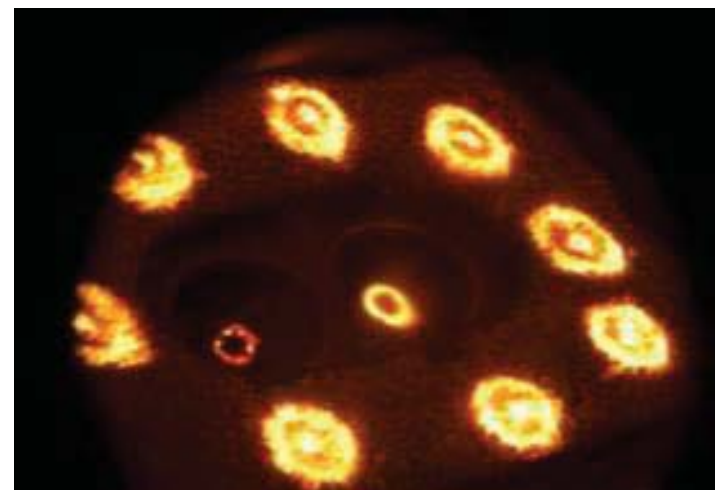


Development of *Directed Vapor* Electron Beam - Physical Vapor Deposition (EB-PVD) Airfoil Environmental Barrier Coating Processing under NASA Programs

- In collaboration with Directed Vapor Technologies, NASA has developed turbine airfoil environmental barrier coating composition coatings using Directed Vapor EB-PVD processing
- Advanced coatings processed for higher TRL ERA combustor and turbine component EBCs (TRL 4-5)

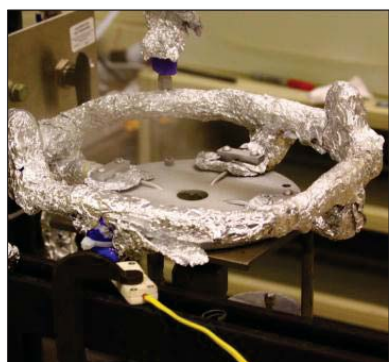


Directed Vapor Processing Systems



Development of *Directed Vapor* Electron Beam - Physical Vapor Deposition (EB-PVD) Airfoil Environmental Barrier Coating Processing under NASA Programs

- EBC recession kinetics testing for CMCs-EBCs in NASA High Pressure Bruner Rig and Laser Steam High Heat Flux Rig Testing

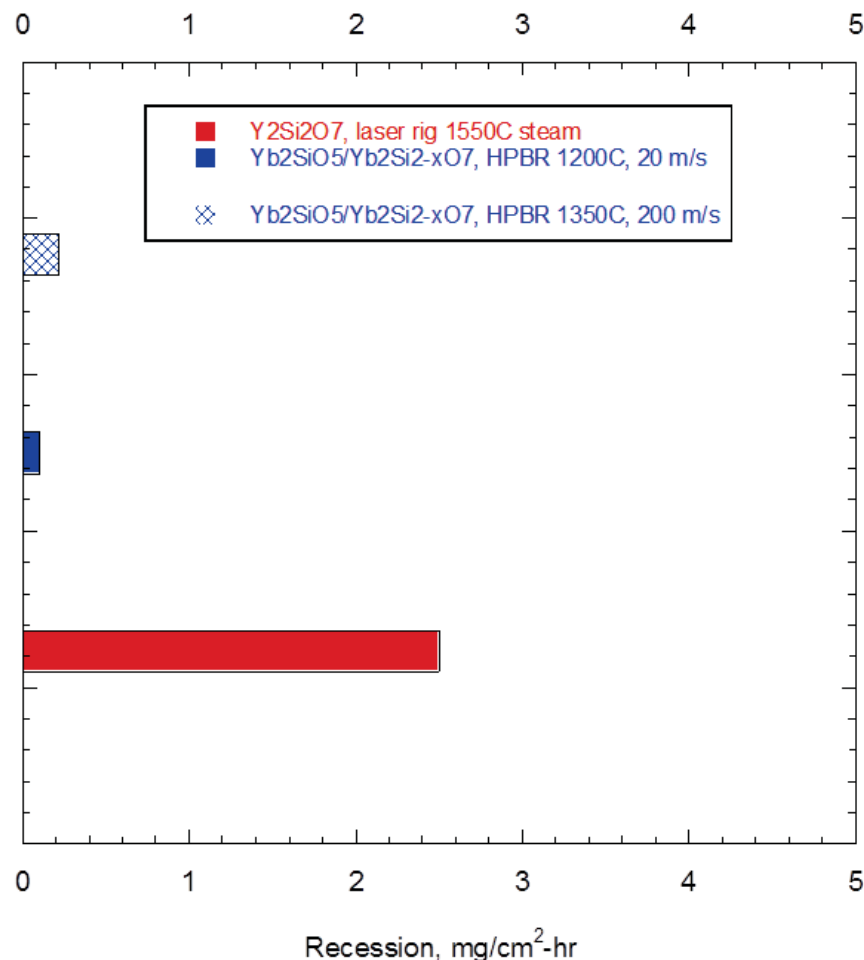


Steam during cooling cycles



High temperature testing with steam flow

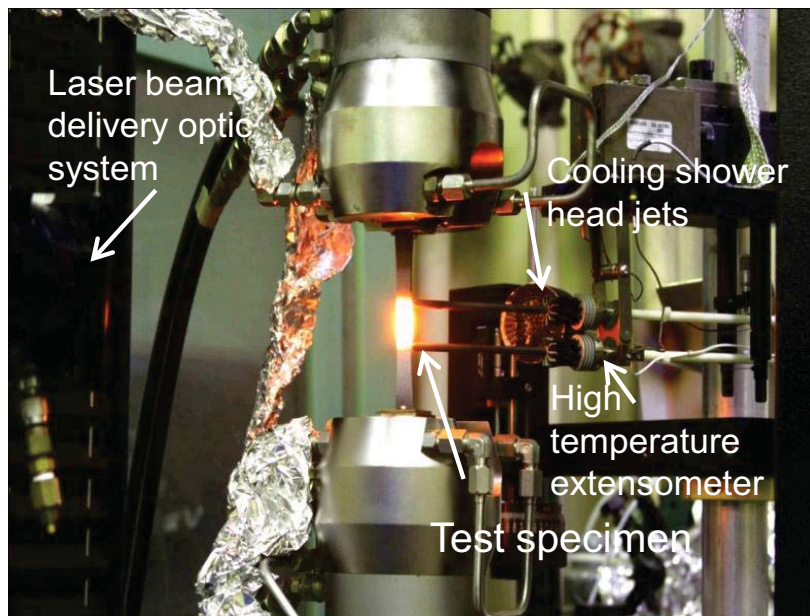
(c) High heat flux and high steam rig



Examples of environmental barrier coating recession in laboratory simulated turbine engine conditions

Thermal Gradient Tensile Creep Rupture Testing of Advanced Environmental Barrier Coating SiC/SiC CMCs

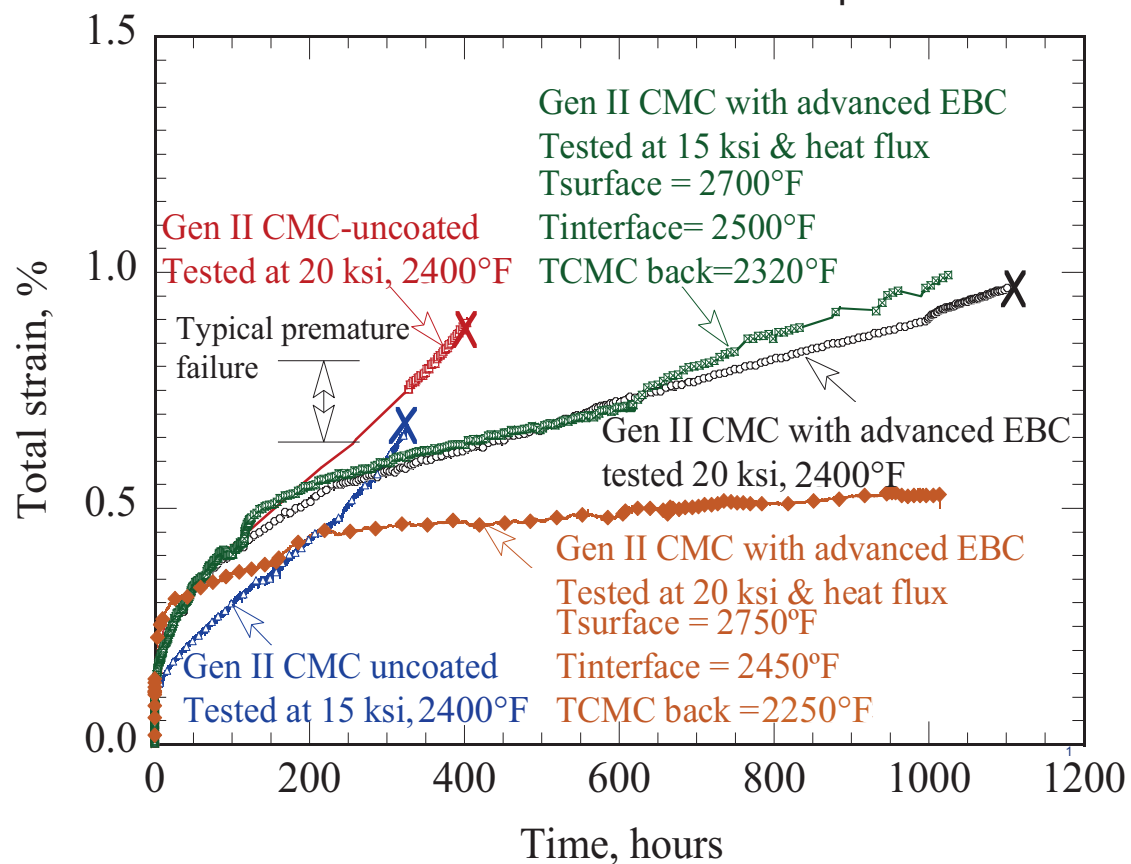
- Advanced high stability multi-component hafnia-rare earth silicate based turbine EBCs have been demonstrated in various long-term creep rupture tests
- EBCs improved the SiC/SiC CMC environmental resistance and durability
- EBC-CMC fatigue - environmental interaction is currently being emphasized



NASA High Heat Flux Tensile creep rupture rig

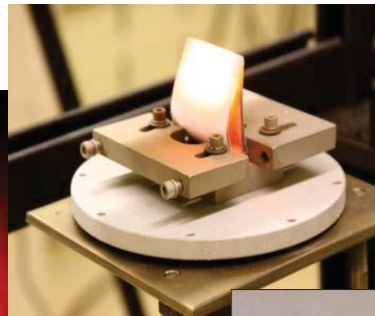


EBC coated tensile specimen



Advanced Rig Tests for SiC/SiC CMC EBC Demonstrations

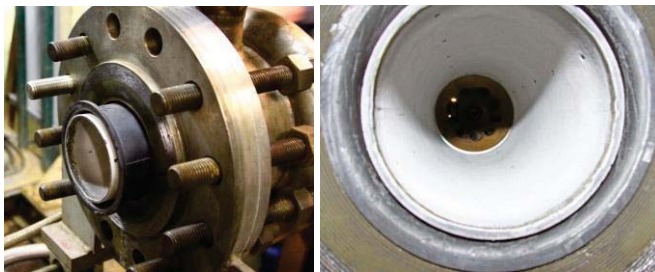
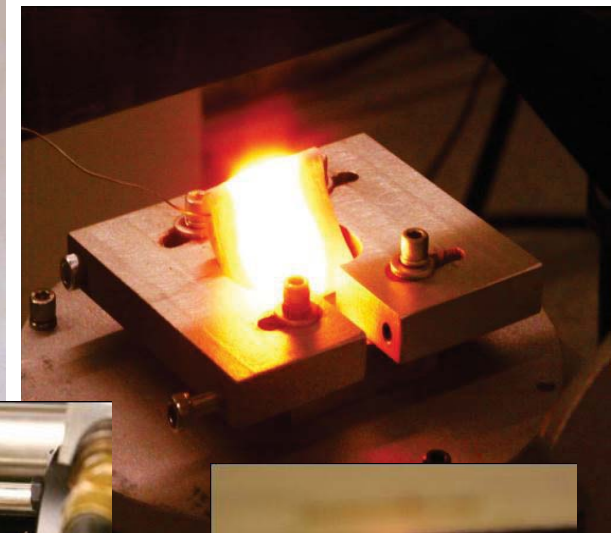
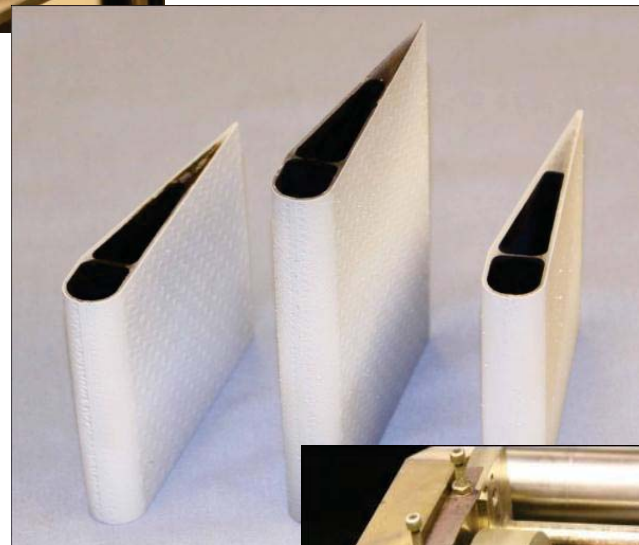
- Advanced EBC coated turbine airfoils, combustor liners and subelements demonstrated in high pressure burner rig and high heat flux laser rig simulated engine environments



50 hr EBC-CMC vane laser rig testing



50 hr EBC-2.5D CMC Sub-element demo in HPBR



NASA EBC coated turbine airfoils and combustor testing





Summary

- **Advanced high temperature SiC/SiC CMC environmental barrier coatings development has a key emphasis on temperature capability and durability**
 - Develop advanced compositions for meeting next generation engine coating and component performance requirements
 - Emphasize advanced turbine CMC airfoils coatings, addressing processing, long-term stability and durability under high-heat-flux and highly loaded conditions
 - Developed advanced combustor and turbine vane EBC component technologies, and demonstrating the full feature EBC - CMC sub-components in relevant rig simulated engine environments
 - Developed EBC systems and subelement testing methods, helping establish property database, and developing life prediction models
 - Current work also focused on thermal - mechanical stress creep-rupture – fatigue behavior of EBC-CMCs, and the stress-environment interactions on component durability



Advanced Environment Barrier Coating Material System Development - Emerging Opportunities

— High stability, low expansion top coat development

- Rare earth dopants and silica clusters along with transition metal oxides for improved temperature and environmental stability
- High melting point, reducing interface reactions – self-forming diffusion and reaction barriers
- Controlled SiO_2 activity, minimizing grain boundary Si segregation, SiO_2 phase formation, and low melting phase formation
- Low thermal conductivity, thin EBC configurations emphasized for both turbine CMC airfoil and advanced combustor applications

— Low stress, strain tolerant interlayer and high strength bond coats

- Prime-reliant coating systems
- High strength and advanced highly intergraded EBC/CMC interface designs
- Self repairing and/or self-growing of slow growth adherent protective coatings, i.e., design of alloys, intermetallic and composites capable of self growing EBCs
- Low expansion, high stability, low diffusivity, low oxygen activity, and oxidation resistance
- High strength and high toughness to achieve maximum energy dissipation, impact and fatigue resistance

— Multifunctional compositions for high temperature sensing, health monitoring, and reduced heat transfer